



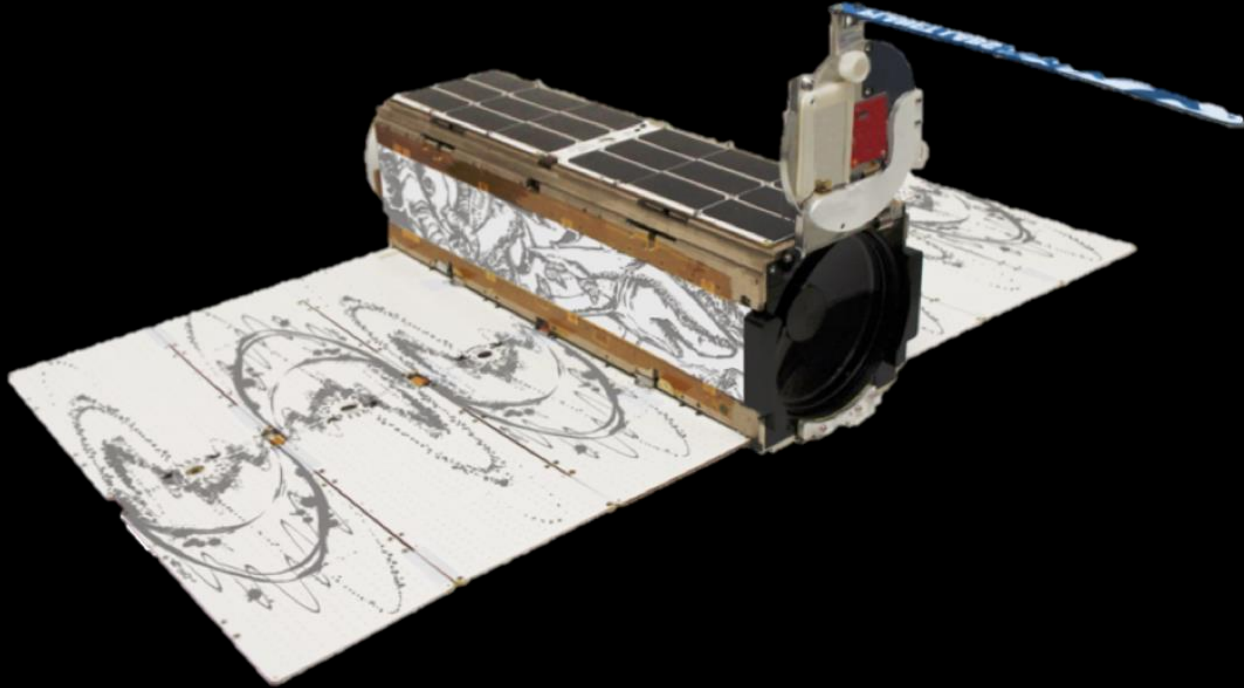
Lunar radiometric calibration on Planet Dove satellites

Arin Jumpasut, Adriana Fukuzato, Joshua Greenberg, Nicholas Wilson

JACIE, Sept 20, 2017

Uluru, Australia, DEC 2, 2015

Dove Satellite



PlanetScope Constellation



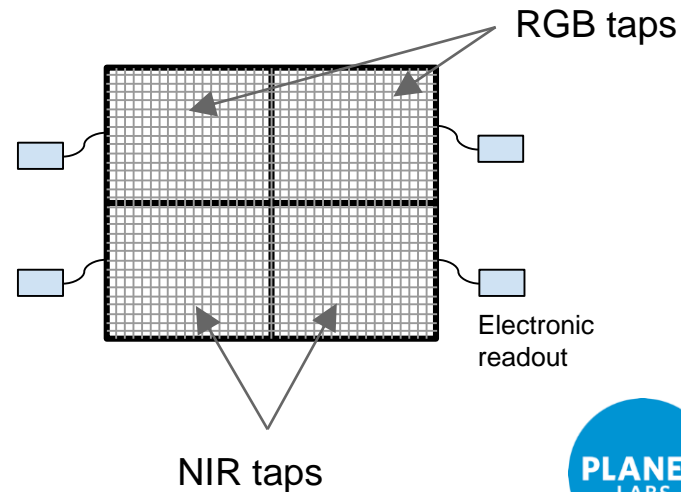
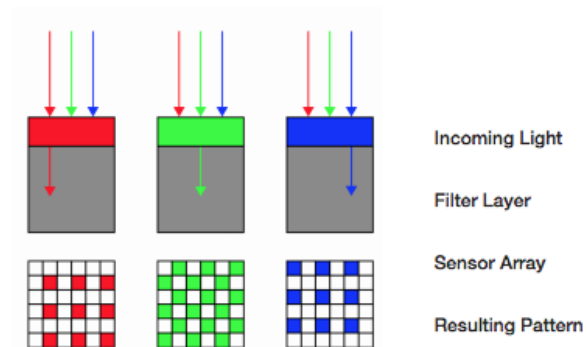
	ISS Orbit	Sun Synchronous Orbit
Expected Lifetime	1 year per satellite	2-3 years per satellite
Mission Continuity	Up to 55 satellite constellation (continually replenish / upgrade satellites)	100-150 satellite constellation (continually replenish / upgrade satellites)
Inclination	52 deg	98 deg
Orbital Insertion Altitude	420km	505km
Ground Sampling Distance (Nadir)	2.7m-3.2m	better than 4m
Sensor Type	Bayer-masked CCD camera	
Spectral Bands	Blue: 420-530nm Green: 500-590nm Red: 610-700nm NIR: 760-860nm	

Image Collection

4-tap Bayer-Masked CCD Array


Bayer Mask

4-Tap Arrangement



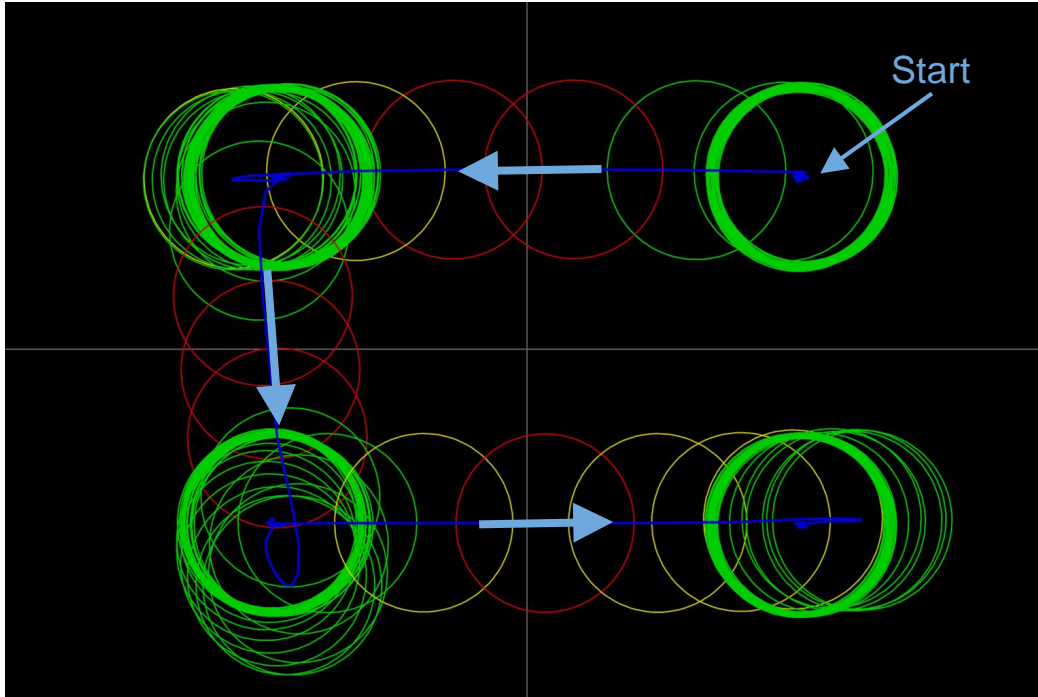


Methodology



Shallow Seas, Bahamas FEB 4, 2016

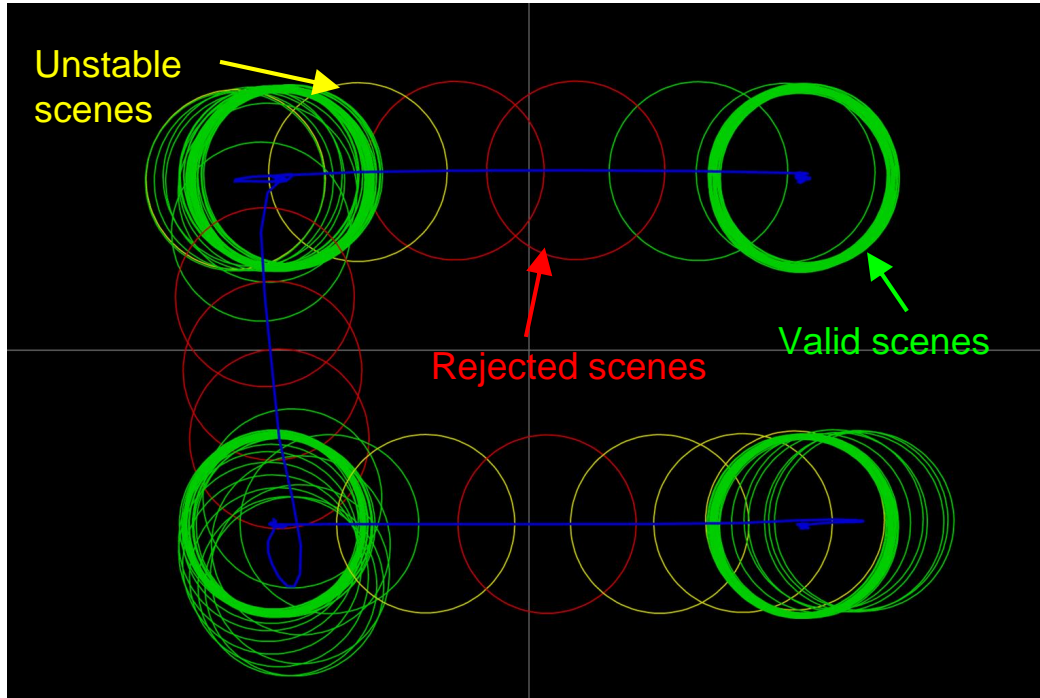
The moon shot manoeuvre



- The aim of the moon shot manoeuvre is to get scenes of the moon completely within each of the four taps
 - Since each of the four taps are effectively independent
 - The top two taps record the RGB bands and the bottom tap the NIR band
 - This is performed when the satellite is in eclipse



The moon shot manoeuvre



- A valid scene is one that is completely within a tap as well as not having a distance too extreme from the mean position
- Unstable scenes are scenes that are completely within a tap (and so useable) but are over a threshold from the mean position (e.g. if the satellite is transitioning between taps)
- Rejected scenes are ones that overlap a tap boundary or are otherwise unuseable.



The moon shot schedule



- During the first full available lunar cycle after commissioning, each satellite takes a full cycle of moon shots
 - This is to build up a baseline of the radiometric response of each new satellite
 - This starts from about 110 degrees phase angle waxing and continues to about 110 degrees phase angle waning
 - The different phases of the moon mean that slightly different points in the dynamic range are being measured and compared against the ROLO model



The moon shot schedule



- Every subsequent lunar cycle, moon shots are only taken at three phase angles in both the waxing and waning parts of the lunar cycle
 - This is to just provide a check that the satellite's radiometric response is stable
 - These are taken at 10, 35 and 70 degrees phase angles in both the waxing and waning portions of the cycle
 - These can provide long term trending data on the satellites



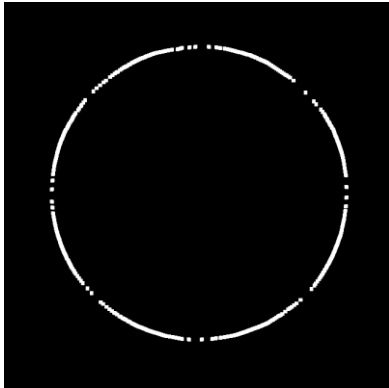
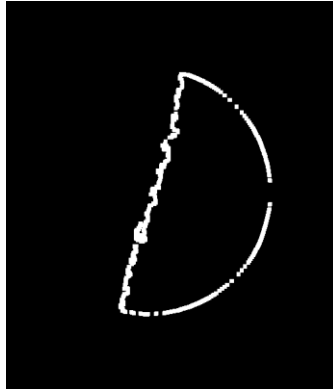
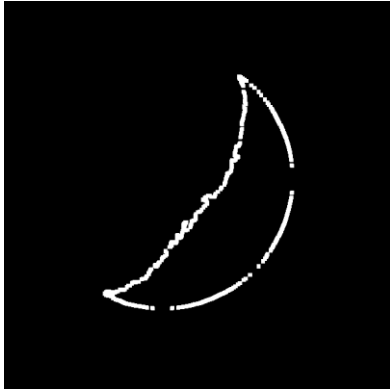
Extraction of the moon disc



- **These examples images are taken from Wikipedia's article on lunar phase**
- Attribution in clockwise order from the leftmost image:
 - By Ian Kirk from Broadstone, Dorset, UK - Here is the obligatory " I gotta a new long lens" shot!, CC BY 2.0, <https://commons.wikimedia.org/w/index.php?curid=30448703>
 - By Daniel Hershman from Federal Way, US - march moon, CC BY 2.0, <https://commons.wikimedia.org/w/index.php?curid=2096667>
 - By Enceladus - Own work, CC0, <https://commons.wikimedia.org/w/index.php?curid=14673815>



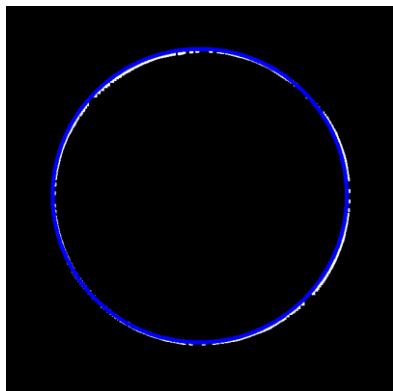
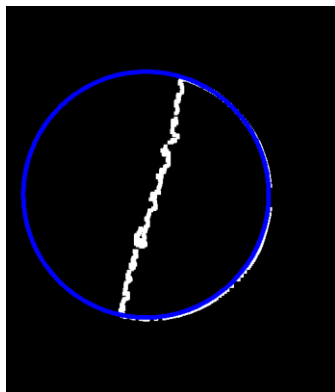
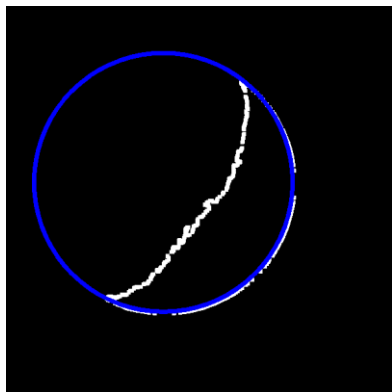
Extraction of the moon disc



- An outline of the per scene algorithm
 - Contour detection to extract pixels at the edge of the pixel
 - Fitting a function to the contour pixels (e.g. an ellipse function or a circle function)
 - Testing that the extracted disc is 'sane' (e.g. within all the taps and with an area within an expected range)



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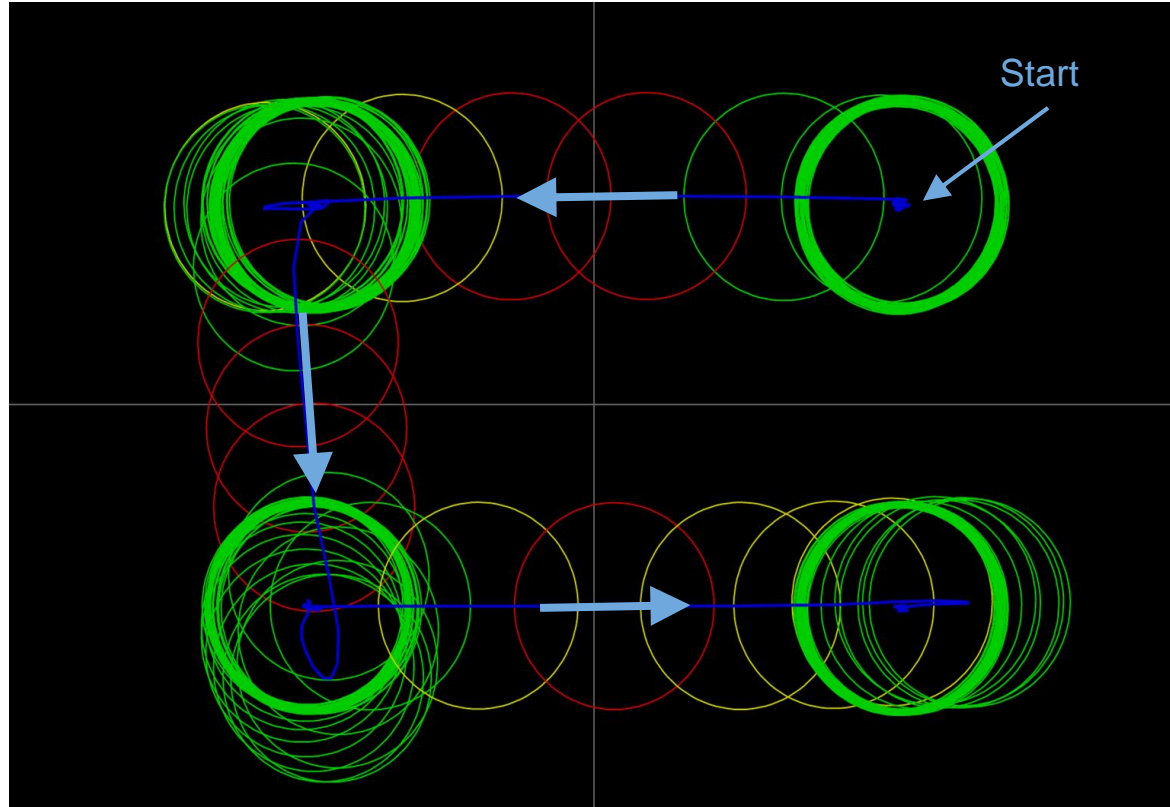
Extraction of the moon disc



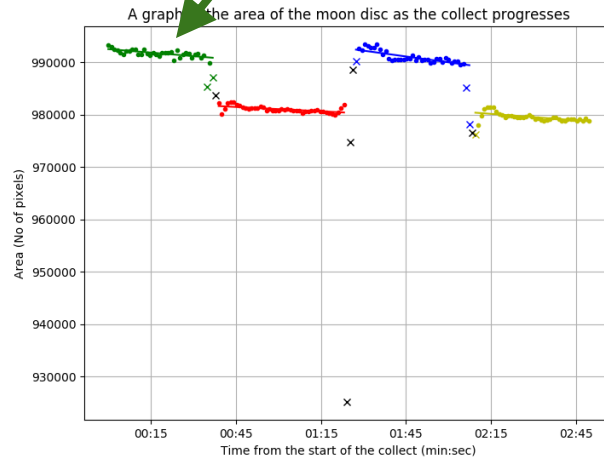
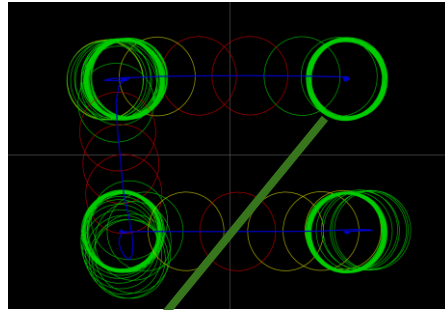
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The moon shot manoeuvre



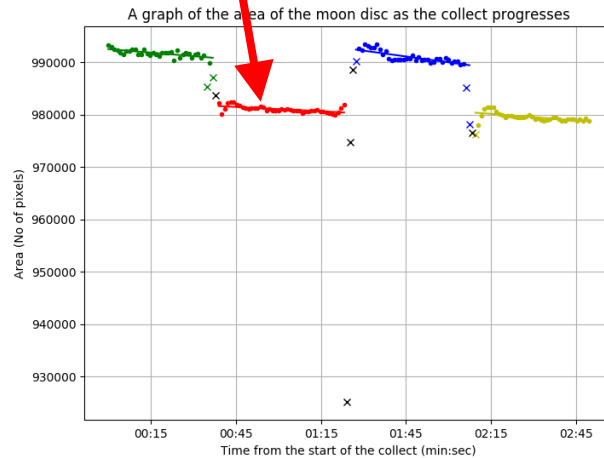
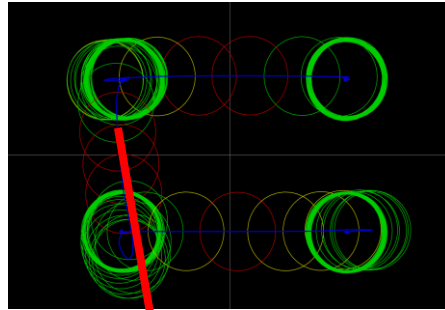
Extraction of the moon disc



- Once the moon disc has been found for each scene, the entire collect can be analysed to reject outliers
 - A linear function is fit to the **area** of the moon disc and outliers are rejected
 - This results in smoother measurement with edge cases being rejected



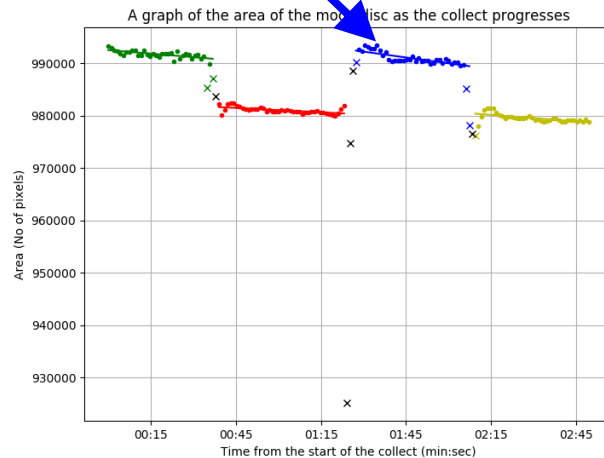
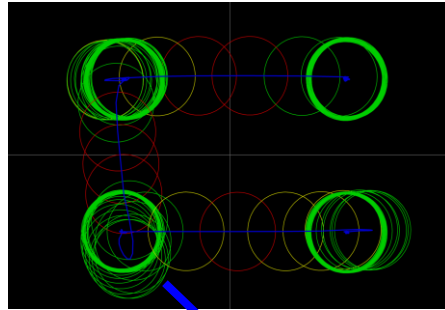
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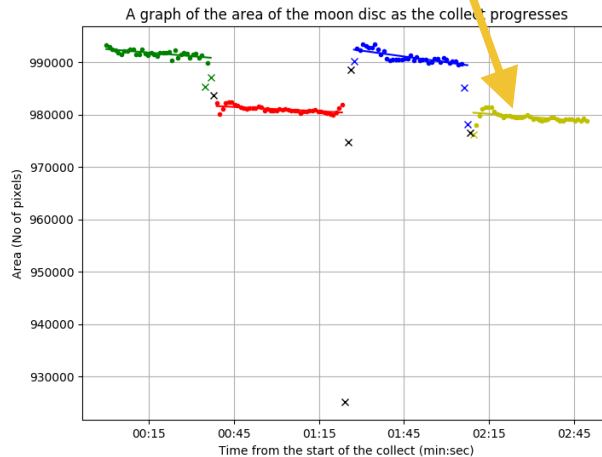
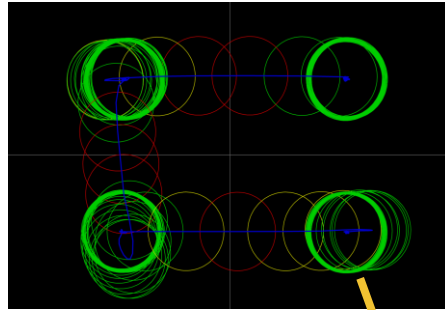
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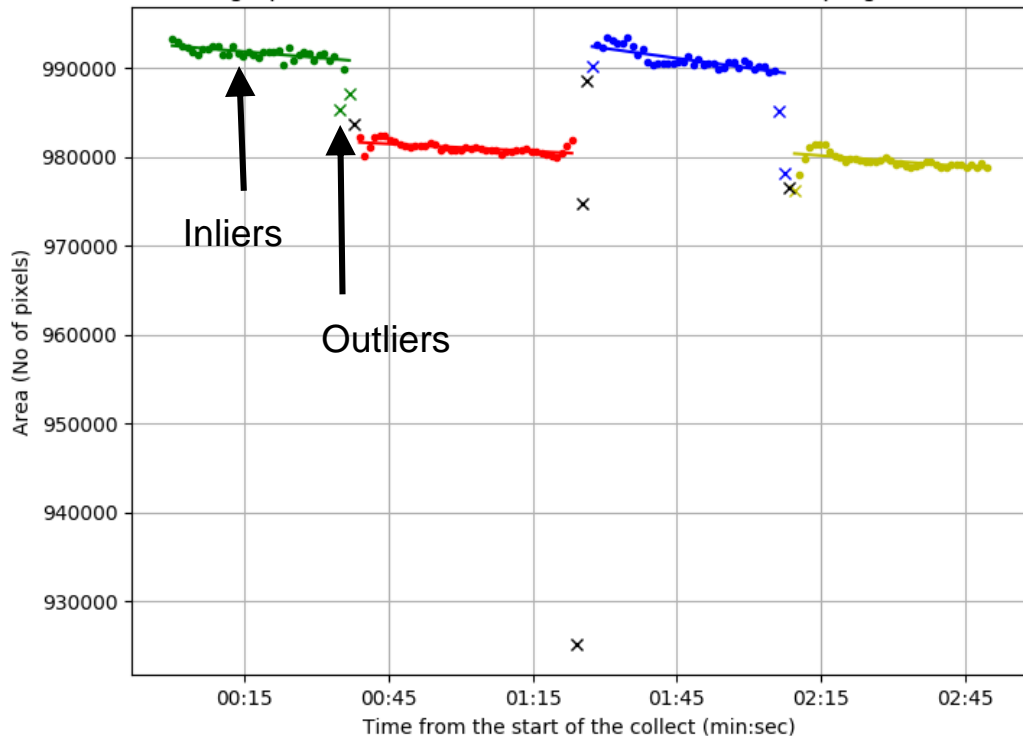
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Extraction of the moon disc



A graph of the area of the moon disc as the collect progresses



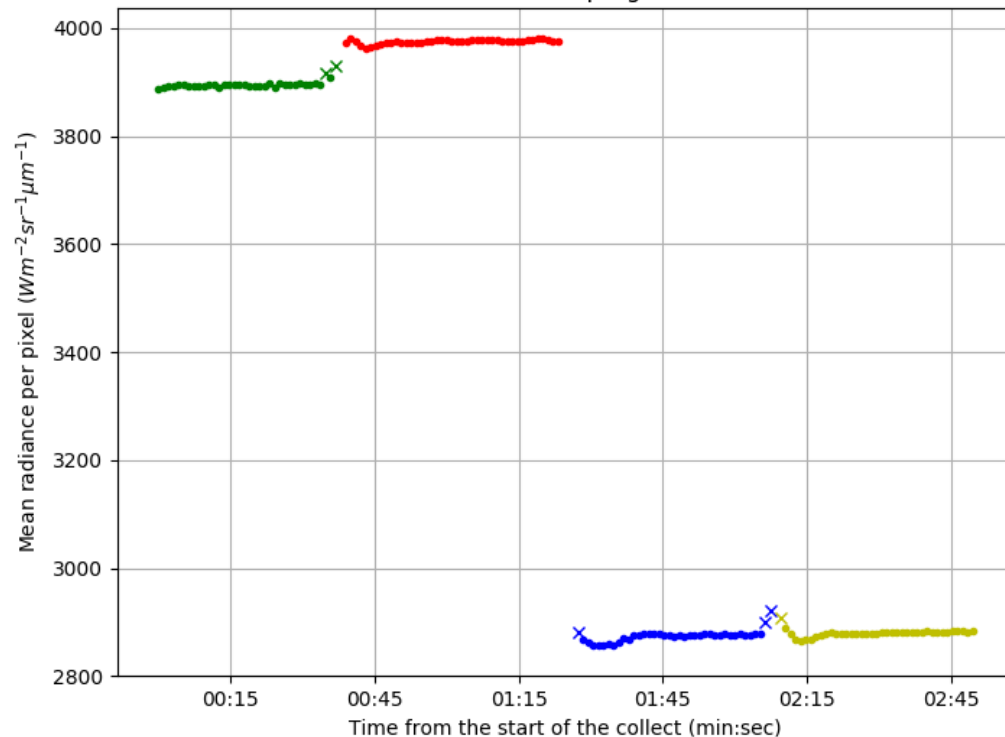
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Extraction of the moon disc



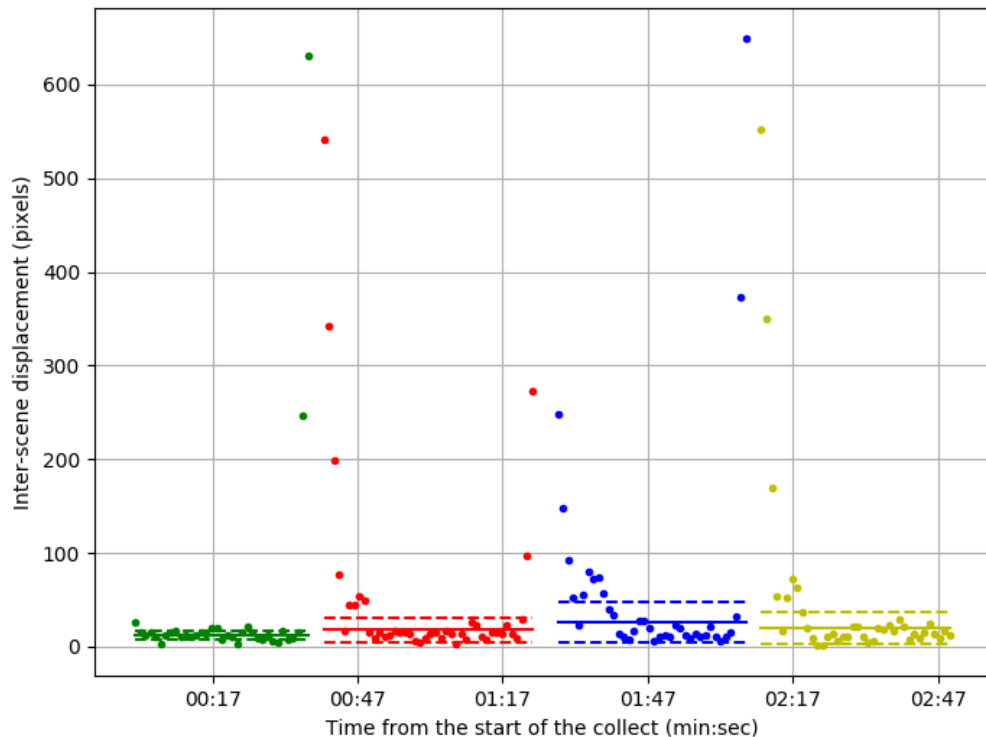
A graph of the mean radiance per pixel of the moon disc
as the collect progresses



- Once the moon disc has been found for each scene, the entire collect can be analysed to reject outliers
 - A linear function is fit to the area of the moon disc and outliers are rejected
 - This results in a stable **radiance** measurement with edge cases being rejected



Collect metrics

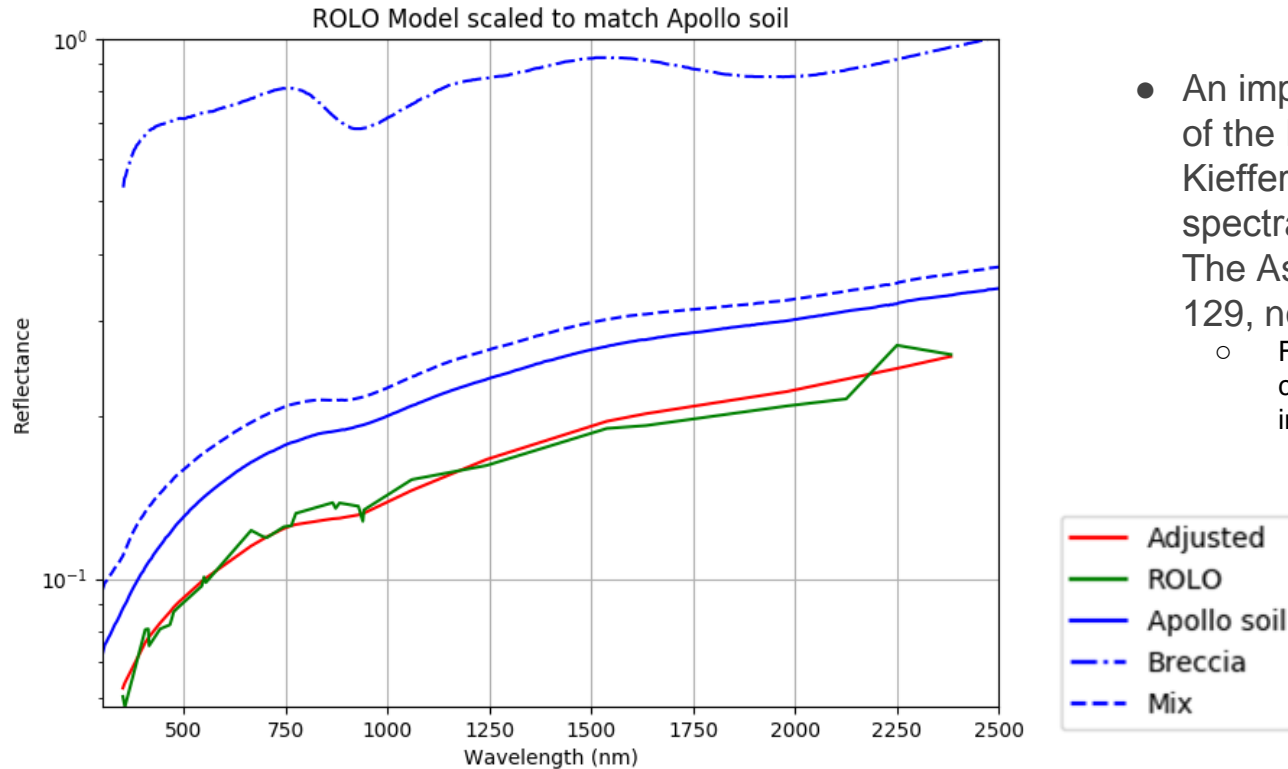


- One final check that we do on the moon collect is to make sure that the satellite is stable when recording each tap
 - This doesn't affect which measurements we use, but is useful for diagnosis of different satellites' performance

— Tap 1 is STABLE (Mean: 17.61, std: 12.53)
— Tap 2 is STABLE (Mean: 12.13, std: 4.94)
— Tap 3 is STABLE (Mean: 25.62, std: 21.70)
— Tap 4 is STABLE (Mean: 19.68, std: 17.04)



Implementation of the ROLO model




- An implementation was created of the ROLO model from H. H. Kieffer and T. C. Stone, “The spectral irradiance of the Moon,” The Astronomical Journal, vol. 129, no. 6, p. 2887, 2005
 - Figure 8 from the paper was re-created to verify the implementation of the ROLO model



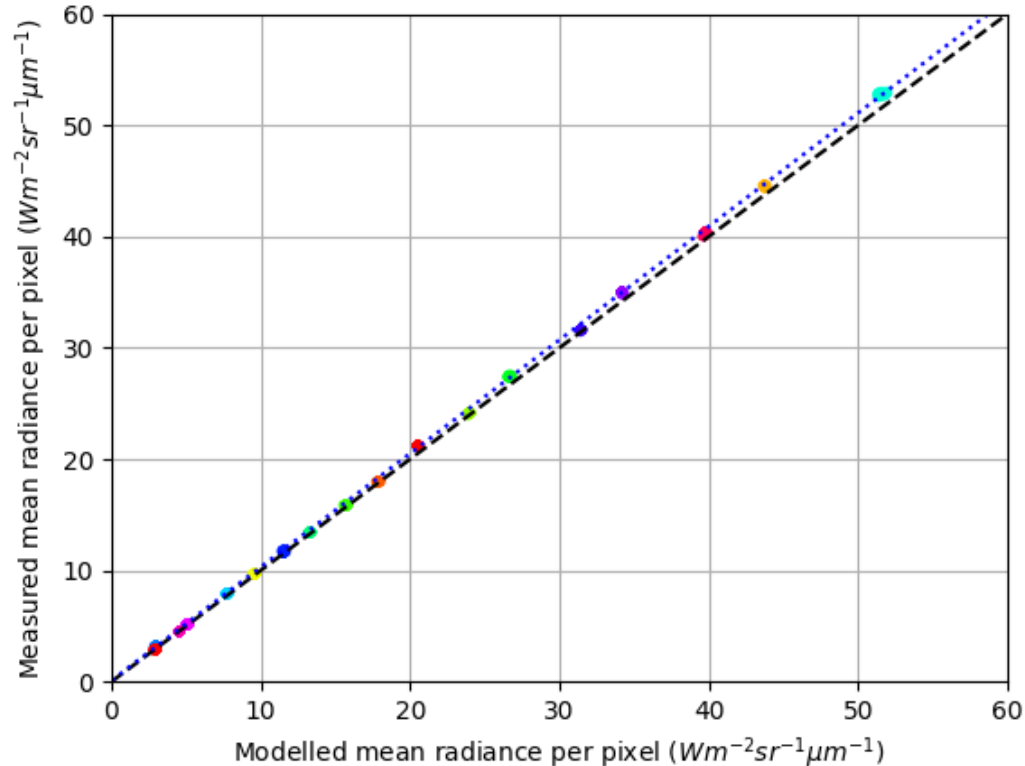


Results



Shallow Seas, Bahamas FEB 4, 2016

Daily moon shot results



- This figure shows the results of an entire moon cycle of daily moon shots.

- Each day's collect is shown in a different colour
- The mean per pixel radiance is used, which is defined as:

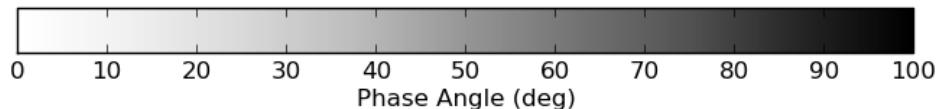
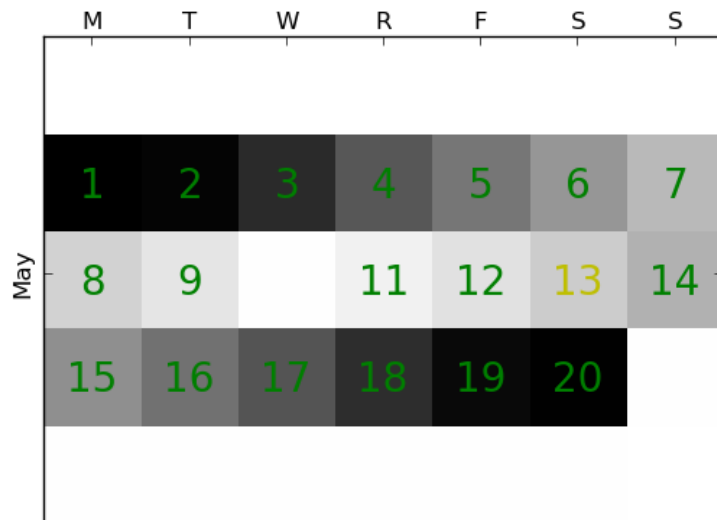
the total integrated radiance over
the entire moon disc

the number of pixels within the
entire moon disc

- There is some deviation from a linear relationship due to some influence from the phase angle that has not been corrected for yet



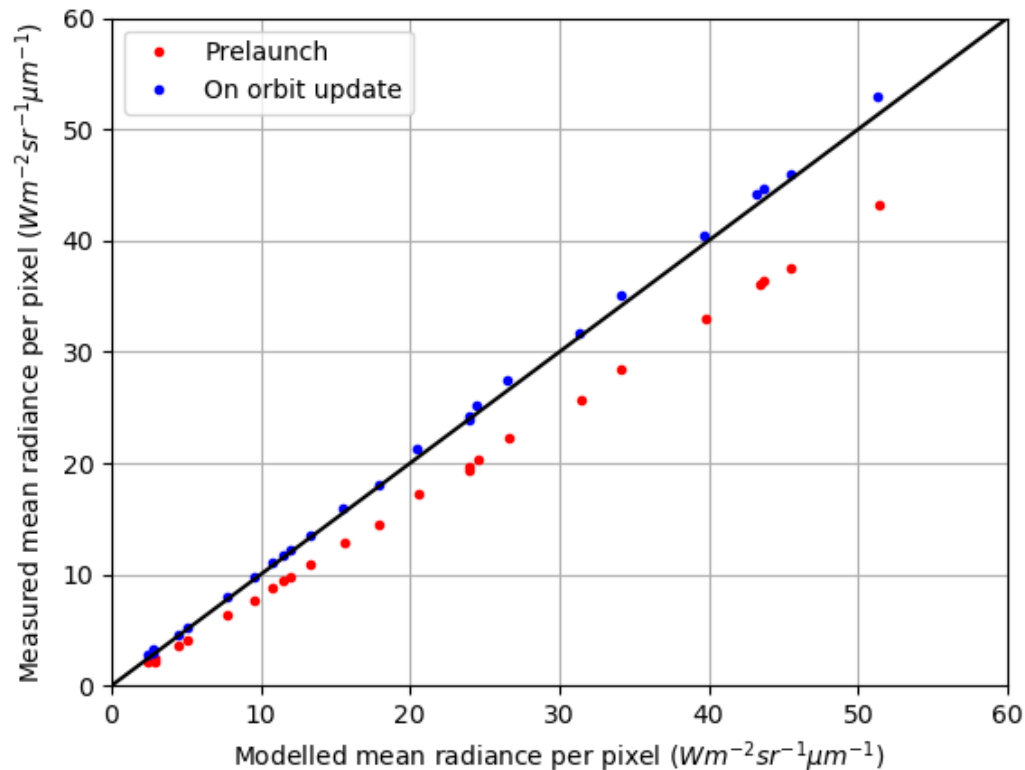
Daily moon shot results



- Each moon cycle, a summary of the satellite's performance is produced to verify that there is enough lunar data
 - The colours are only based on the pointing stability of the satellite.
 - Due to the amount of satellites, summary graphs like this are important



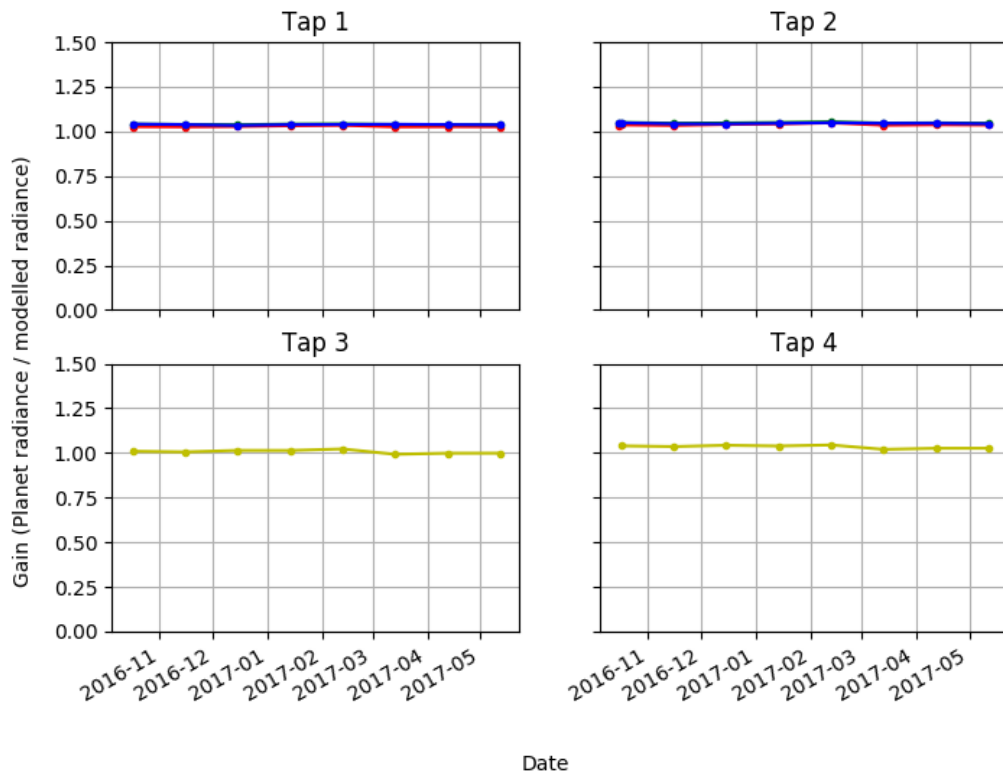
On orbit calibration vs prelaunch



- Five months after the launch of flock 3p satellites, the first on orbit update was performed
 - The results of the on orbit update vs the prelaunch calibration on lunar data can be seen
 - Currently the update is based on simultaneous crossovers with the RapidEye fleet



Monitoring of satellite health

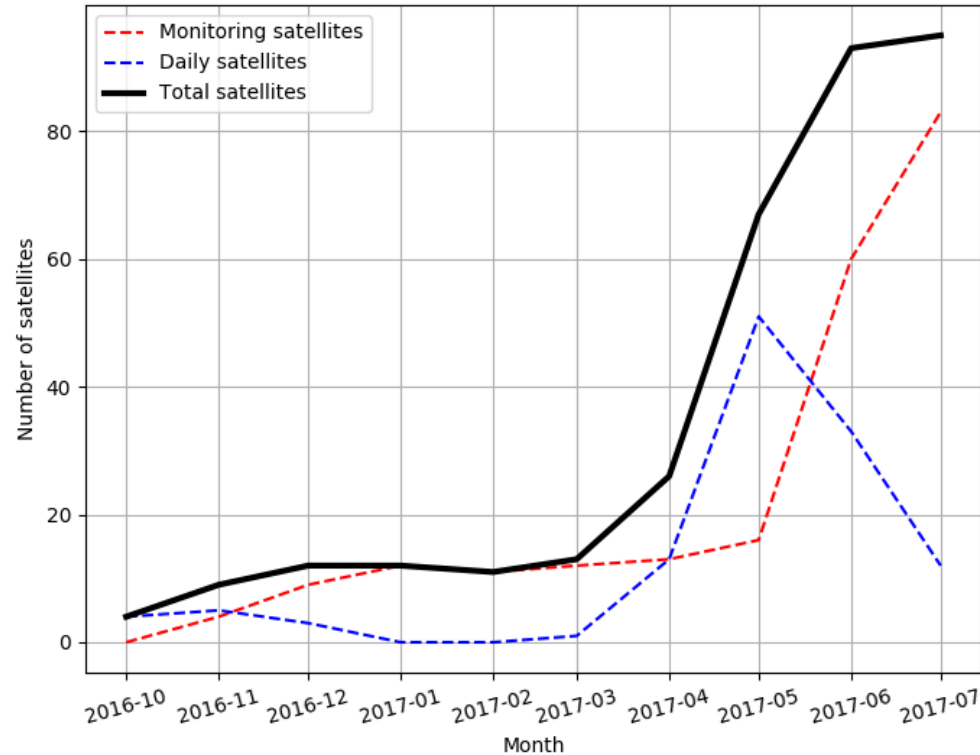


- The lunar data is used to monitor long term trends and satellite health
 - The first satellites started this process in Q4 of 2016 and have had continuous monitoring moon shots since then
 - Moon shots have helped to diagnose and validate fixes to misaligned star cams and other hardware problems
 - This graph shows the results for a satellite's four taps in all the bands



Conclusions

Number of satellites imaging the moon



Conclusions



- There will be an archive of moon shots maintained for each satellites
 - At least one cycle of daily moon shots and a continuous history of monitoring moon shots since launch
 - If required, e.g. anomalies were detected in the monitoring moon shots, more frequent moon shots can be scheduled
 - From July 2017, there are 95 satellites taking moon shots each month (daily and monitoring)
 - And during the month of May 2017, there were 51 satellites taking daily moon shots
 - This will be useful for long term monitoring of the satellites
 - Moon shots are simpler to schedule regularly than simultaneous crossover events
- Currently this data is used for long term monitoring of the satellites
 - But eventually use this data could be used for relative calibration of the satellites
 - The effect of phase angles needs to be modelled over the full range of phase angles
 - It could also be combined with Earth facing data for absolute calibration of the satellites

